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CONFERENCES AND SYMPOSIA

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Celebrating 50 years of the laser
(Joint scientific session of the Physical Sciences Division
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and the A M Prokhorov General Physics Institute, RAS,
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A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and the scientific councils of the P N Lebedev Physical Institute, RAS and the A M Prokhorov General Physics Institute, RAS dedicated to the 50th anniversary of the advent of the laser was held in the conference hall of the Lebedev Physical Institute on 21 April 2010.

The following reports were put on the session's agenda posted on the website www.gpad.ac.ru of the Physical Sciences Division, RAS:

(1) **Alferov Zh I** (A F Ioffe Physical-Technical Institute RAS, St. Petersburg) "Semiconductor heterostructure lasers";

(2) **Bagaev S N** (Institute of Laser Physics, Siberian Branch, RAS, Novosibirsk) "Ultrahigh-resolution spectra and their fundamental application";

(3) **Masalov A V** (P N Lebedev Physical Institute, RAS, Moscow) "Optical Department of the Lebedev Physical Institute: early work on lasers";

(4) **Garnov S V, Shcherbakov I A** (A M Prokhorov General Physics Institute, RAS, Moscow) "Laser sources of megavolt terahertz pulses";

(5) **Sergeev A M, Khazanov E A** (Institute of Applied Physics, RAS, Nizhny Novgorod) "Structural functions of a developed turbulence";

(6) **Popov Yu M** (P N Lebedev Physical Institute, RAS, Moscow) "The early history of semiconductor lasers";

(7) **Manenkov A A** (A M Prokhorov General Physics Institute, RAS, Moscow) "Self-focusing laser pulses: current state and future prospects".

The papers written on the basis of reports 3, 4, 6, and 7 are published below. A comprehensive version of report 5 prepared in the form of a review paper is published in this issue of *Physics–Uspekhi* on p. 9.

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Optical Department of the Lebedev Physical Institute: early work on lasers

A V Masalov

1. Introduction

After the successful creation of masers in the mid-1950s, the idea of implementation of quantum oscillators radiating in the optical range, i.e., lasers, was in the air. The term 'laser' had not yet gained acceptance by that time. Many people aspired to accept the challenge of nature, to implement population inversion in a medium, and demonstrate the light amplification in the optical wavelength range. In this case, the desire to be the very first, which is natural for researchers, speeded up the execution of such endeavors. Nowadays, too, the 'virus of priority' is a powerful incentive for the cognition of nature. Discussed in this report is the pioneering work on the development of lasers performed by the staff members of the optics-related laboratories of the Lebedev Physics Institute (LPI). Although the term 'very first' is applicable to these investigations, they are valued primarily for their impact on the future development of laser physics and laser technology.[1]

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[1] Many researchers are infected with the 'virus of priority'; everyone may give examples. However, among outstanding scientists there are those who have never carried the virus of priority. An instructive example is Grigorii Samuilovich Landsberg. In the year of the discovery of combination scattering of light, when G S Landsberg and his closest colleague Leonid Isaakovich Mandel'shtam analyzed experiments on light scattering in quartz, they were perfectly aware that they were dealing with a new phenomenon of a fundamental nature. And yet they were far from the idea of 'staking out' their finding, being instead concerned with the verification

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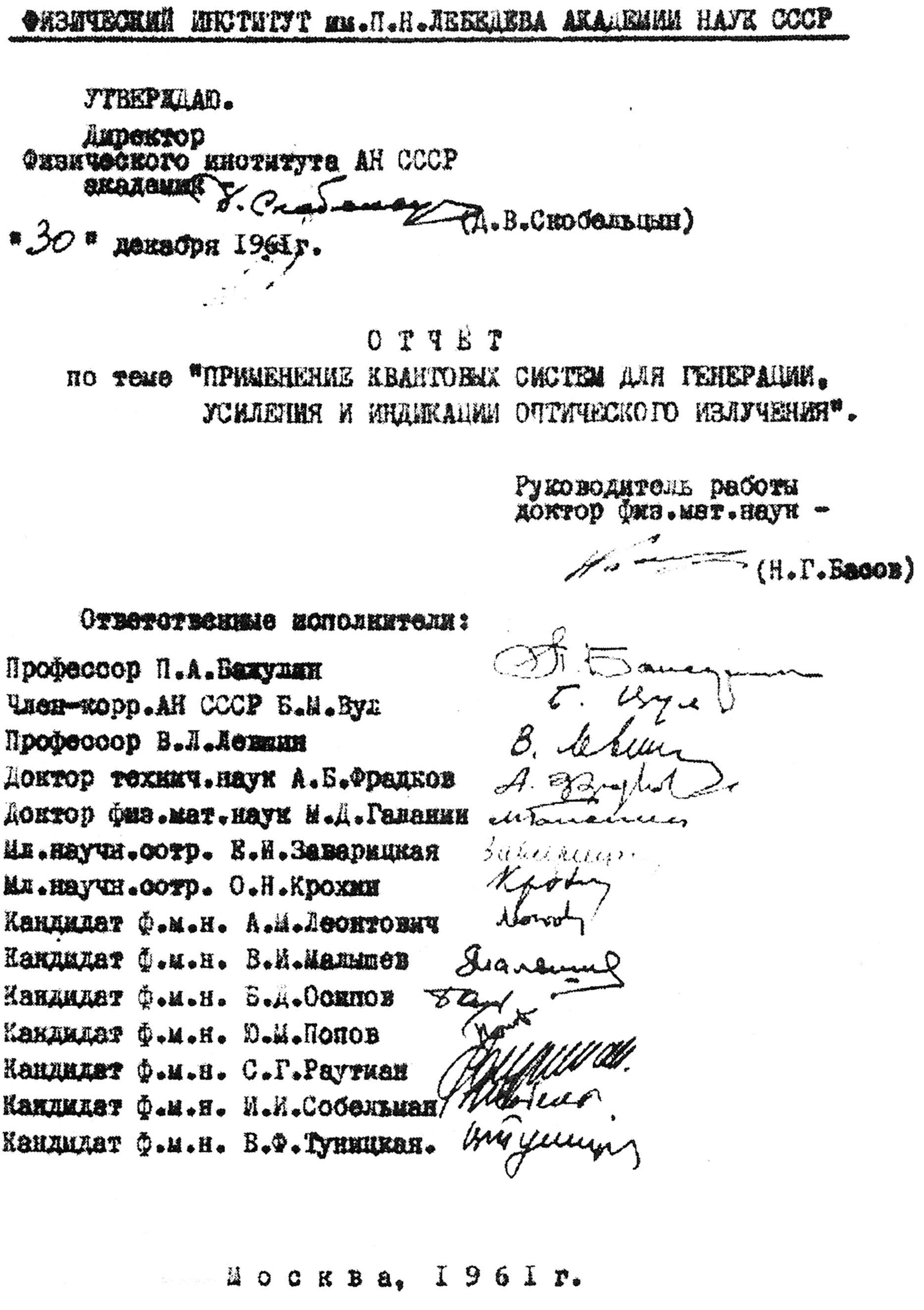

ФИЗИЧЕСКИЙ ИНСТИТУТ им.П.Н.ЛЕБЕДЕВА АКАДЕМИИ НАУК СССР

УТВЕРЖДАЮ.
Директор
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по теме "ПРИМЕНЕНИЕ КВАНТОВЫХ СИСТЕМ ДЛЯ ГЕНЕРАЦИИ, УСИЛЕНИЯ И ИНДИКАЦИИ ОПТИЧЕСКОГО ИЗЛУЧЕНИЯ".

Руководитель работы
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Кандидат ф.м.н. И.И.Собельман
Кандидат ф.м.н. В.Ф.Туницкая.

Москва, 1961 г.

Title page of the report issued in 1961.

of the experiments and the consistency of the physical picture of the phenomenon. The same cannot be said about C V Raman, whose name was given to the combination light scattering. Another example of a person uninfected by the virus of priority — Mikhail Dmitrievich Galanin.

Early in 1959, Nikolai Gennadievich Basov set up a program labeled Photon at the P N Lebedev Physical Institute of the USSR Academy of Sciences, whose line of research was formulated in its title: "Application of quantum systems to the generation, amplification, and detection of optical radiation.'' N G Basov provided State support for this research, which was embodied in the relevant governmental Resolution of April 1960. By that time, N G Basov and his colleagues had already conceived the ideas of how to implement semiconductor lasers. The Photon project extended the scope of the quest for gain media suited for operating in optical quantum generators (OQGs) to include fluorescent crystals and gases. Involved in the work were highly experienced staff members — 'opticians' — now referred to as brilliant researchers and outstanding scientists, who made significant contributions to science. The photograph above shows the title page of the report written late in 1961, listing the scientists responsible for project execution. There we see the names of opticians as well: P A Bazhulin, V L Levshin, M D Galanin, A M Leontovich, V I Malyshev, S G Rautian, I I Sobel'man, V F Tunitskaya — more than half of the list.

The staff members of the optics-related laboratories at LPI performed several pioneering investigations in the development of lasers. Some of these priority achievements are listed in this paper, which may be termed either as 'the very first', or as 'the first in the USSR'.

It was in the framework of the Photon project that the first work on the list of pioneering achievements described below was carried out. The question is how the first ruby laser was developed in this country.

2. Ruby laser

The first Soviet publication about the implementation of a ruby laser and the properties of its radiation was prepared by M D Galanin and his colleagues A M Leontovich and Z A Chizhikova [1]. The paper was submitted to *JETP* on 18 May 1962. According to the authors, the ruby laser itself was brought into service in September 1961. By that time it had already been in operation in the USA. The first publication [2] about light amplification, by Theodore Maiman, was published in *Nature* in 1960. In the same year, Maiman implemented the oscillation regime [3]. Arthur Schawlow was hot on the trail and put into operation the ruby laser (also in the USA) [4]. Therefore, the paper by M D Galanin et al. may be referred to as the first one in the USSR. There is unconfirmed information about the making of a ruby laser by L D Khazov in the State Optical Institute (SOI) in mid-1961. Unfortunately, attempts to find documentary evidence of this have not met with success.[2]

The creation of the Soviet ruby laser required that crystal 'growers' synthesize ruby samples of unconventional quality. The watchmaking industry of that time made use of ruby crystals with a chromium concentration of 2.5%, and such crystals were available. However, to achieve lasing called for larger crystals with a lower chromium concentration. Such crystals were grown for the project by staff members of the Special Design Bureau (OKB-311) A S Bebchuk and Yu N Solov'eva. Ensuring optical crystal uniformity was a special concern. The circumstances were rather favorable as regards flash lamps employed for pumping ruby lasers. Such lamps were produced for airplane lights used on night flights. The mirrors of the first lasers were silver layers deposited directly on the polished ends of a ruby rod in a vacuum facility. In the LPI there were such homemade facilities, which demanded certain skills for their operation. Therefore, the first LPI ruby laser resulted from the achievements of Soviet industry and the experience of advanced science.

According to A M Leontovich and Z A Chizhikova, participants in the creation of the ruby laser who are still alive, shortly after the laser was put into operation on Soviet crystals, a specimen of American laser ruby rod fell into their hands. They obtained lasing on that rod as well.

The international scientific community was made directly aware of the Soviet ruby laser achievements at the Third International Congress on Quantum Electronics in Paris in 1963 [5]. The text of this report published in the congress proceedings is an example of an in-depth and comprehensive analysis of laser radiation (this text is reproduced in Appendix I to the paper by A M Leontovich and Z A Chizhikova published in this issue (p. 77).

Noteworthy in the history of the invention of the ruby laser is the fact that ruby — the crystal of chromium-doped corundum — had found itself in the view of American and Soviet researchers as the most attractive candidate for lasing even several years prior to their success. One may read about this both in the report on the Photon project and in N G Basov's memoirs, which were published in book [6]. The expertise and intuition of the pioneers did not let them down.

The significance of the implementation of the first laser at the LPI is hard to overestimate. A multitude of familiar and unfamiliar people came to the Laboratory of Luminescence to look at the 'ruby OQG'. Owing to the authors' openness, before long the laser was reproduced in many laboratories, and investigations of lasers and their improvement and application were placed on a broad footing shortly thereafter.

3. Photodissociation laser

Putting forward the idea of a photodissociation laser and the development of an optical quantum generator relying on the photodissociation mechanism of inversion production is the second example of pioneering laser research. The proposal to employ the photodissociation mechanism to achieve lasing was put forth by S G Rautian and I I Sobel'man [7]. They hypothesized that one of the products of molecular dissociation under short-wavelength irradiation would find itself primarily in an excited state. Broad molecular absorption lines and narrow atomic emission lines in dissociation products promised the high gain coefficients required for lasing. This idea was set forth at length in the foregoing 1961 LPI report. In the experimental quest that followed, the members of V I Malyshev's group directed their attention to the NaI and TlI molecules, which glowed rather brightly due to dissociation; these were the emission lines of sodium (yellow) and thallium (green). However, the first lasing based on the photodissociation mechanism was obtained in 1964 by J Kasper and G Pimentel with CF_3I and CH_3I molecules [8]. Kasper and Pimentel came across the high brightness of the radiation in experiments involving the analysis of infrared emission spectra of these media dissociated by ultraviolet radiation: this was the 1.315-μm emission line of atomic iodine. This 'prompt' from the Americans enabled V I Malyshev's group members to implement the photodissociation laser within a few months. That was the first work on lasers based on the photodissociation mechanism of pumping a laser medium in our country [9]. This mechanism opened up the line of research into different versions of iodine photodissociation lasers in our country,

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[2] See the archival documents of the SOI first published in this issue of *Physics–Uspekhi*. (*Editor's note*.)

including those powered by explosive pumping (see the paper by V S Zuev [10]).

4. Ultrashort laser pulses

Among the important achievements in the area of laser development, mention should be made of the work of V I Malyshev and his colleagues, which lies at the origin of lasers generating ultrashort radiation pulses. The case in point is the implementation and investigation of the laser self-mode-locking regime.

It became obvious after the advent of the first ruby laser, as might be recalled, that pulsed solid-state lasers generate, as a rule, irregular sequences of laser spikes — free-running lasing spikes — for several hundred microseconds. The principle of *Q*-switching was formulated only a short time later, which made it possible upon implementation to concentrate the energy of numerous laser spikes in one high-power 'giant pulse' with a duration of several nanoseconds or tens of nanoseconds. *Q*-switched lasers promised a rise in radiation intensity by several orders of magnitude, and the development of *Q*-switching means started making rapid strides. The first *Q*-switches were electrooptical shutters, which necessitated a pulsed multikilovolt supply. To achieve *Q*-switching, advantage was also taken of a rotating reflection prism (rotation frequency amounted to several dozen kilohertz). N G Basov suggested to V I Malyshev that he should develop jointly with chemists a *Q*-switch in the form of a bleachable dye solution. On Malyshev's initiative, the staff members of the LPI Optical Laboratory A S Markin and V S Petrov also got involved in the work. By 1966, such *Q*-switches were developed in the Optical Laboratory of the LPI in collaboration with chemists of the Research Institute of the Chemicophotographic Industry (NIIKHIMFOTO), I I Levkoev and A F Vompe [11]. The *Q*-switch comprised a compact glass cell with a dye solution, which was placed into the laser cavity and did not necessitate control. Quite suitable here was the experience of chemists in developing media which darkened under high-power irradiation (primarily from the radiation of a nuclear bomb explosion). When studying lasers with a bleachable dye, they discovered the regime of self-mode-locking, i.e., the regime whereby the 'giant' pulse acquired additional structure in the form of a train of pulses of picosecond duration. The radiation intensity at the peak of a picosecond pulse was several orders of magnitude higher than the intensity of an ordinary 'giant' pulse. The implementation of self-mode-locking was first reported by American researchers in 1966 [12]. V I Malyshev and A S Markin were so close to the independent discovery of this regime that they promptly carried out research work on this subject [13] and submitted it for publication in September 1966. Among the authors of that paper was Tat'yana Ivanovna Kuznetsova, who provided the theoretical elaboration of the subject and subsequently performed numerous theoretical investigations into ultrashort light pulses. The indicated paper thereby turned out to be the first publication on the implementation of laser self-mode-locking in this country. Dye No. 3955 (a polymethine dye) developed for these purposes for neodymium lasers, which disseminated to many laboratories from Malyshev's hands, permitted executing a wealth of brilliant work with picosecond pulses. Today, after several improvements the laser self-mode-locking regime has reached the femtosecond duration range, and femtosecond lasers are employed in a diversity of domains of science and technology.

5. Copper vapor laser

After the first advances in the development of lasers, N G Basov initiated the quest for new laser media, in particular, in the gas phase. This research was taken up by G G Petrash and his collaborators in the Optical Laboratory of the LPI. They decided in favor of a copper vapor laser. The copper vapor laser with highly attractive output energy characteristics was made by W T Walter (USA) in 1967 [14]. A disadvantage of this laser was the necessity of external heating of the active medium to a temperature of 1500 °C. Petrash and his colleagues came up with the idea of a self-heating laser and implemented it. To do this they had to design a new discharge tube. Even in the first paper on the self-heating copper vapor laser they reported an average output power of 15 W [in two lines: green (510.5 nm), and yellow (578 nm)] for a pulse repetition rate of 20 kHz; the peak power ranged up to 200 kW and the practical efficiency up to $\approx 1\%$ [15]. As a result, the energy characteristics of the copper vapor laser placed it among the 'workhorses' of laser technology. In the course of subsequent development of the laser, the authors managed to attain an almost diffraction-limited radiation divergence by using an unstable cavity [16]. They also implemented a brightness amplifier based on a self-heating copper vapor tube [17], and made a laser projection microscope with a brightness amplifier as its key element [18]. The decisive contribution of G G Petrash's group to the development of the copper vapor laser has been recognized worldwide.

6. Intracavity laser spectroscopy

The idea of intracavity laser spectroscopy was conceived and realized at the LPI late in the 1960s. The idea of detecting weak spectral lines in absorption media placed into a laser cavity arose with Al'bert Fedorovich Suchkov [19], a staff member of the Laboratory of Quantum Radiophysics. A F Suchkov's proposal was underlain by the idea that laser radiation traverses a cavity several thousand (or more) times to accumulate the weak effect of absorption by the medium. Before long, the first experiment demonstrating the high sensitivity to spectral losses was carried out on A F Suchkov's initiative (and with his participation) in E A Sviridenkov's group at the LPI Laboratory of Luminescence [20]. Use was made of a neodymium laser and a V I Malyshev type diffraction spectrograph. The authors took advantage of their expertise to eliminate parasitic spectral-selective losses in the laser in order to record only the controllable losses. This result inspired the participants in the work, and they developed a high-sensitivity spectroscopic technique which has come to be known as intracavity laser spectroscopy (ILS). Numerous examples are known today of employing the ILS technique with other broadband lasers for the detection of lines in a diversity of substances. The priority of E A Sviridenkov's group in the development and dissemination of this technique has been recognized worldwide. In the 1980s, a series of studies on ILS was nominated for the USSR State Prize. However, this work was not awarded the prize owing to personal relations outside the team of authors.

7. Mechanism of CO_2 laser operation

Since its invention in 1966, the electric discharge CO_2 laser has attracted the attention of researchers due to the novelty of its spectral range (10.6 μm) and the uncommonness of the inversion production mechanism: this was a laser operating by transitions between *vibrational* levels of the molecule.

Optimization of the CO_2 laser ran into difficulties because of the lack of understanding of the mechanism responsible for the production of inversion between vibrational levels in a gas discharge. The situation became clear with the emergence of a paper by N N Sobolev and V V Sokovikov [21] and Ref. [22] that followed. The authors compared data on the average electron energy in the discharge with the energy dependence of the excitation cross section for the corresponding molecular vibrational levels and saw that the electron impact mechanism is highly efficient. In this case, the inversion between vibrational levels is produced due to collisions with atoms and molecules. When these papers appeared, a start was made on a targeted theoretical description of the CO_2 laser and a new impetus was given to experiments aimed at its improvement. Notably, the USSR's first CO_2 gas-dynamic laser was put into operation in the framework of this work [23].

8. Conclusions

Summarizing the foregoing material, one may draw a conclusion on what underlay the success of Soviet science in the development of lasers.

- In the USSR there existed a large community of highly qualified scientists, which was permanently fed by scientific personnel from institutes of higher education (the Moscow Institute of Physics and Technology (MIPT), M V Lomonosov Moscow State University, the Moscow Engineering Physics Institute, etc.). From MIPT alone (MIPT was founded for preparing researchers in physics) several hundred graduates came to the LPI during the post-war years. The leaders of the laser program, N G Basov and A M Prokhorov, could rely on the scientific schools nourished by S I Vavilov, G S Landsberg, and L I Mandel'shtam at LPI.
- A system of financing the research had functioned in the USSR. The government responded to the needs of science and stimulated scientific progress. New facilities were commissioned to promote laser research: buildings on the LPI territory, branches of the LPI in Troitsk with accommodation for scientists, the Institute of Spectroscopy, the Polyus Scientific Production Association, and other laser research institutes.
- USSR industries were capable of providing the requisite components and instruments for research; in the USSR there were works for creating big research facilities and technologies for producing unique materials.

Notwithstanding the known shortcomings of the governance of that time, a strategically weighed program of scientific and technological development existed in the country. Laser research was a part of this program.

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Laser methods for generating megavolt terahertz pulses

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1. Introduction

The development of terahertz (THz) electromagnetic radiation sources is related to new methods and avenues of basic research in physics, chemistry, biology, and medicine, which have been making rapid strides during the last decade, as well as to new methods in different areas of applied research, including those related to new industrial technologies and security issues (see book Ref. [1] and references cited therein).

Terahertz radiation opens new paths and fresh unique possibilities for studying the properties and structure of substances and objects in the heretofore practically inaccessible spectral–temporal domain. Recording the probing terahertz pulses transmitted or reflected by an object and their subsequent amplitude–time and spectral analysis permits acquiring data about the object parameters and the substance properties in the terahertz range, as well as about the processes occurring therein, with a high (pico- and subpicosecond) temporal resolution. Along with use in basic research, terahertz pulses find practical applications in

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